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Proper motion, age and initial spin period of PSR J0538+2817 in S147

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ABSTRACT

We present results of timing observations of the 143-ms pulsar J0538+2817 that provide a proper motion measurement which clearly associates the pulsar with the supernova remnant S147. We measure a proper motion of 67^{+48}_{-22} mas yr^{-1}, implying a transverse velocity of $v = 385^{+260}_{-130}$ km s^{-1}. We derive an age of the pulsar and S147 of only 30 ± 4 kyr which is a factor of 20 times less than the pulsar's characteristic age of $\tau_c = 620$ kyr. This age implies an initial spin period of $P_0 = 139$ ms, close to the present pulse period and a factor of several larger than what is usually inferred for birth periods. Implications for recent X-ray detections of this pulsar are discussed.

Subject headings: pulsars: general; pulsars: individual (J0538+2817); stars: neutron; supernova remnants

1. Introduction

The determination of the birth properties of pulsars is of crucial importance in understanding both the physics of core-collapse supernovae as well as the population and evolution of a radio pulsar. The initial spin period of pulsars, P_0, is particularly difficult to measure

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as it requires the knowledge of the pulsar's age, τ, and its spin-down behaviour. It is usually assumed that the observed evolution of the spin-frequency $\nu = 1/P$ can be described by a power-law $\dot{\nu} \propto -\nu^n$, where n is the so-called *braking index*. The initial spin period can then be calculated from

$$P_0 = P \left[1 - \frac{n-1}{2} \frac{\tau}{\tau_c} \right]^{\frac{1}{n-1}} \tag{1}$$

where $\tau_c = P/2\dot{P}$ is the *characteristic age* of the pulsar. The characteristic age is a good estimator for the true age of the pulsar, $\tau_c \approx \tau$, under the assumptions that $P_0 \ll P$ and that the spin-down is due to magnetic braking for which $n = 3$.

Since the use of the characteristic age, rather than the true age, can lead to considerable errors, it is desirable to have an independent age measurement. The age of a supernova remnant (SNR) that originated in the same explosion as the pulsar, can serve as such an estimator but the only pulsar for which the age of an associated SNR is clearly known, is the Crab pulsar. From the observation of the explosion in A.D.1054 and a measured braking index of $n = 2.51(1)$, the initial spin period is computed to be P_0 =19 ms (Lyne et al. 1993). It may also be possible to measure a proper motion of a pulsar associated with a SNR. If this transverse motion is directed away from the center of the SNR, then this is strong evidence that the pulsar is genuinely associated with the remnant. It also allows one to determine the age of both the pulsar and the SNR by comparing the present offset from the center with its speed. As SNRs typically fade away after $\sim 100,000$ yr, pulsars genuinely associated with SNRs are necessarily young. Such pulsars, however, often show rotational instabilities in the form of glitches and/or timing noise (e.g. Lyne et al. 1995) which makes the measurement of proper motion via timing observations usually a difficult task. Interferometric measurements offer a solution but so far it has only been possible for PSR B1951+32 in CTB 80 for which an initial spin period of $P_0 = 27(6)$ ms was derived (Migliazzo et al. 2002).

In this work we present a timing proper motion measurement for the 143-ms pulsar J0538+2817 which was found within the boundaries of G180.0−1.7, also called S147 (Anderson et al. 1996). The SNR S147 has a prominent shell structure with a radius of $\theta = 83(3)$ arcmin (Sofue et al. 1980). With an estimated age of ~ 100 kyr (e.g. Kundu et al. 1980) it is considered to be one of the oldest well-defined SNRs in the Galaxy, although other authors derived much younger ages (e.g. 20 kyr, Sofue et al. 1980). Therefore, S147 has been studied rather extensively at radio frequencies (e.g. Fürst et al. 1982). Very recently, X-ray observations with CHANDRA have revealed a structure interpreted as a pulsar wind nebula (Romani & Ng 2003) while XMM-Newton observations revealed pulsed X-ray emission from the surface (McGowan et al. 2003). In the following we describe our timing observations and data analysis which leads to a proper motion measurement which clearly associates the pulsar with SNR S147. We hence obtain accurate estimates of the age of the pulsar and derive

its initial spin period. The results are finally compared to the recent X-ray observations.

2. Observations and Data Analysis

The observations were made with the 100-m Effelsberg radiotelescope from April 1994 at 1410 MHz and with the 76-m Lovell telescope at Jodrell Bank from March 1996 at 606 MHz and 1400 MHz. At both telescopes, two circularly polarized signals were mixed down to intermediate frequencies, detected and incoherently de-dispersed in hardware using filterbanks before sub-integrations of 15 sec (Effelsberg) and 60 sec (Jodrell Bank) were written to disk for off-line processing. All data were time-stamped with clock information provided by local H-maser clocks which were later synchronized to UTC by using signals from the Global Positioning System (GPS) satellites. Details of the observing systems can be found in Anderson et al. (1996) and Hobbs et al. (2003a).

The data from both telescopes were first processed to a common time resolution of 238.3 μs before being subjected to the same template matching procedure which used identical templates to determine the pulse times-of-arrival (TOAs). Since PSR J0538+2817 shows mode-changing, exhibiting two distinct profiles which differ in the relative height of the two prominent components (Anderson et al. 1996), we applied a proven technique that uses two different, carefully created templates for the given modes (see e.g. Stairs et al. 2000). Any possible remaining effects due to the occurrence of mixed-mode profiles are accounted for by adopting relatively large minimum errors of $\Delta t \geq 180\mu$s (Effelsberg) and $\Delta t \geq 130\mu$s (Jodrell Bank), respectively. The success of this procedure is notable by the fact that no arbitrary clock offsets between the telescopes or profile modes were needed in the further timing analysis.

In a first step of the timing analysis using the DE200 planetary ephemerides, the dispersion measure (DM) was determined by fitting for DM and a simple spin-down model to data obtained with the Lovell telescope at 606 and 1400 MHz over a small period of time. The DM value was then held fixed for the subsequent analysis. Like many other young pulsars, PSR J0538+2817 shows long-term timing noise visible in the timing residuals. Hobbs et al. (2003a) developed a new technique to remove such timing noise, allowing one to reliably separate the signature due to proper motion. Applying this technique, the transverse proper motions have been determined for more than 300 pulsars and excellent agreement is found for those pulsar where interferometric measurements are available (Hobbs et al. 2003a,b). We applied this technique, before fitting to a spin-down model which now included proper motion and a second period derivative. Iterative tests were made to check the robustness of the obtained solution which also studied the effects of omitting and including different parts

of the data in the analysis. We do not believe that the non-zero second period derivative is due to magnetospheric braking, therefore we do not attempt to calculate a braking index, n (see Hobbs et al. 2003a).

As the pulsar lies close to the ecliptic with an ecliptic latitude, β, of only $\beta = 4^\circ.9$, position and proper motion measurements in the latitudinal direction are necessarily much less accurate than those in ecliptic longitude. In order to minimize covariances between the astrometric parameters, fits were made in ecliptic coordinates using the software package `TEMPO`[5], resulting in post-fit residuals shown in Fig. 1. The final spin and astrometric parameters are presented in Table 1. Quoted uncertainties are derived from twice the formal `TEMPO` error and standard Monte-Carlo simulations. Procedures for the latter are detailed in Lange et al. (2001) and results obtained for proper motion are shown in Fig. 2.

3. Results and Discussion

As can be seen from Table 1 and Fig. 2, we have obtained a proper motion measurement for PSR J0538+2817. Whilst the movement in ecliptic longitude is measured to high significance, the uncertainty for the proper motion in latitude is much larger. With a probability of 78%, the proper motion is positive in latitudinal direction, making the pulsar moving in the right quadrant on the sky to be consistent with a movement away from the center of S147. We measure a position angle of P.A.= $311^\circ{}^{+28}_{-56}$. The obtained proper motion is consistent with a comparison of the interferometric position obtained by Anderson et al. (1996) and our present timing position.

Using the measured values, we can compute the pulsar's motion in the past and compare it to the location of the center of the SNR. Fitting a circular shape to the radio contours of S147 over a frequency range from 430 MHz to 4750 MHz (Kundu et al. 1980, Sofue et al. 1980, Angerhofer & Kundu 1981, Fürst et al. 1982, Fürst & Reich 1986) we determine the SNR center to be at $\lambda_{SNR} = 85^\circ.57(1)$ and $\beta_{SNR} = 4^\circ.44(1)$ which agrees well with the center determined by Sofue et al. (1980) at 4750 MHz only. We mark the central position on the 2.7-GHz map obtained by Fürst & Reich (1986) shown in Fig. 3. We also mark the position of the pulsar 30 kyr ago as computed from the measured proper motion ($\lambda_{30k} = 85^\circ.57(3)$, $\beta_{30k} = 4^\circ.5(5)$). It is clear that the previous position of the pulsar agrees very well with the center of the SNR, strongly suggesting that the pulsar was born in the same explosion that created S147, about 30,000 years ago.

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[5]`http://www.atnf.csiro.au/research/pulsar/timing/tempo`

Assuming that the pulsar was born at the center of S147, we use the offset of the pulsar from this position, $\Delta\Theta = 2.18(4) \times 10^6$ mas and the measured proper motion to determine a true age of pulsar and remnant of $\tau = 33^{+17}_{-9}$ kyr. The uncertainty in this age is dominated by the error in the proper motion measurement in latitudinal direction. In order to derive more accurate estimate, we can use the offset and motion in longitudinal direction only. This results in an age of $\tau_\lambda = 30 \pm 4$ kyr, confirming that the kinematic age of the pulsar is dramatically smaller than the characteristic age of $\tau_c = 618$ kyr. The only assumption made in deriving this age is that the pulsar was born in the center of the SNR.

Anderson et al. (1996) already discussed the possible association of PSR J0538+2817 with S147 in detail and concluded that an association is plausible. They based their arguments on the proximity of the pulsar to the SNR center and the consistent distance estimates for both pulsar and SNR. The distances estimated for S147 ranging from of 0.8 to 1.6 kpc are well consistent with the dispersion measure distance of the pulsar, i.e. $d = 1.2$ kpc as derived from the NE2001 model (Cordes & Lazio 2002). At this distance, our proper motion measurement yields a transverse speed of $v = 385^{+260}_{-130}$ km s^{-1} which is in excellent agreement with mean observed velocity of pulsars (Lyne & Lorimer 1993). Given the position of the pulsar within the SNR boundaries and a normalized angular distance of only $\delta = \Delta\Theta/\Theta = 0.43(2)$ away from the center, and its location in the Galactic anti-center region where we find only a rather sparse population of known SNRs and pulsars, an association seemed indeed very likely. This is now confirmed by the pulsar's movement away from the center.

Further independent evidence is available that the characteristic age is much larger than the true age of the pulsar. Firstly, while some authors estimate a blast wave age of S147 in a range from 80 kyr to 200 kyr (e.g. Kundu et al. 1980), Sofue et al. (1980) estimated an age of only 20 kyr. Even though these age estimates for SNRs depend also on the density of the ambient interstellar medium and are known to be highly uncertain (e.g. Fürst & Reich 1986), all values are lower than τ_c, and the latter estimate agrees indeed very well with our findings. Given this young age of the SNR, the well defined shell structure appears less surprising. If the explosion occurred in a low-density, hot stellar wind cavity blown up by the progenitor star, the expansion will not be describable by a Sedov-phase but will be free until it reaches the cavity boundaries (E. Fürst, private communication). At a distance of 1.2 kpc, the observed SNR radius corresponds to ~ 30 pc, implying an expansion velocity of 1000 km s^{-1} in the free expansion phase. Future CO observations may be able to reveal the wind cavity.

Secondly, we have access to polarization information for the radio emission of PSR J0538+2817 obtained by Mitra et al. (2003), who measured a rotation measure of RM$=-7\pm$

12 rad m^{-2}. The pulsar exhibits an extremely high degree of polarization of 92(2)%. While this is not uncommon, it is usually found in young sources (e.g. Morris et al. 1981), again supporting a young age of the pulsar.

Finally, we can compare our results to recent X-rays observations. Romani & Ng (2003) reported the discovery of a faint nebula surrounding the pulsar. They interpret this nebula as an equatorial torus, supporting the association of pulsar and S147. In their calculation they assumed a pulsar age of 100 to 200 kyr, but we can derive consistent results with our smaller derived age of $\tau = 30$ kyr with a somewhat smaller ISM density. The orientation of their modelled torus with a symmetry axis located at position angle $\Psi = 154(6)^\circ$ (measured N through E) and $\xi = 100(6)^\circ$ (into plane of the sky) is consistent with the position angle swing measured for our polarization data. Applying a rotating vector model (Radhakrishnan & Cooke 1969), we find a best fit for a magnetic inclination of $\alpha \sim 95^\circ$ and an impact angle of $\sigma \sim 2^\circ$ although the uncertainties are considerable. These findings support Romani & Ng's interesting conclusion derived from the torus geometry that the velocity direction appears to be nearly aligned with the rotation axis of the pulsar. However, with a pulse width of about 40° and such a geometry, one may expect to observe also emission from the opposite magnetic pole. This is not the case, but the emission beam may not be circular and/or the emission beam could be patchy (Lyne & Manchester 1988). We also note that the bilateral symmetry axis of S147 appears to be very nearly parallel to both the symmetry axis of the torus and the proper motion direction of the pulsar. While the remnant is somewhat asymmetric about the orthogonal axis, the center of the explosion could in principle deviate from the SNR center which is determined by the sharp circular rim. However, it is reasonable to assume that the explosion center is located on the symmetry axis between the determined SNR center and the current pulsar position. In such a case, the age of the pulsar would be even younger, and our conclusions would be essentially unaffected.

Equally intriguing is the comparison of our results with those by McGowan et al. (2003) who detected pulsed X-ray emission from PSR J0538+2817. Their data are well explained by blackbody radiation from a heated polar cap. However, using the dispersion measure distance the derived temperature is significantly higher than predicted by standard cooling theories. This discrepancy can be reduced by using atmospheric fits, but with a pure-H non-magnetized atmosphere McGowan et al.'s result still falls above the expected temperature. In their analysis McGowan et al. used the characteristic age of the pulsar, and the high temperature indeed suggests that the true age of the pulsar is much smaller. Using our derived age of $\tau = 30$ kyr, the temperature from the atmospheric fit falls well below the standard cooling curve. However, this fit also produces a distance which is much smaller than the dispersion measure estimate. A proper modelling of the observed X-ray spectra needs to include the surface magnetic field of $B = 7.3 \times 10^{11}$ G, which may change the

results considerably (e.g. Pavlov et al. 2001, Zavlin & Pavlov 2002). This is important since with such a low temperature one would be forced to consider the presence of exotic cooling processes. Interestingly, a similar conclusion has been reached recently by Slane et al. (2002) for PSR J0205+6449 associated with 3C58 (but see also Yakovlev et al. 2002).

Pavlov et al. (2002) studied CHANDRA data of the neutron star 1E 1207.4−5209 which is likely to be associated with SNR PKS 1209−51/52. They also find a characteristic age which is much larger than that estimated for the SNR, suggesting a long birth period of the neutron star. Romani & Ng already already pointed out that the initial spin period of PSR J0538+2817 is likely to be large and close to the present value. Using our age estimate we derive an initial spin period of $P_0 = 139.6$ ms ($n = 3$), which is insensitive to the actual choice of the braking index as the ratio of $\tau/\tau_c = 0.05$ is very small (e.g. $P_0 = 139.6$ ms for $n = 10$ and $P_0 = 139.8$ ms for $n = 0.5$). It has been attempted to estimate the initial spin period for seven radio pulsars (see Migliazzo et al. 2002 and references therein) but apart from the results for the Crab (based on the known age of the SNR and pulsar) and PSR B1951+32 in CTB 80 (based on kinematic age derived from proper motion), all estimates rely on less certain ages estimated for associated SNRs. It appears that the initial period of those pulsars is $P_0 \leq 60$ ms. An exception is PSR J1124−5916 with $P_0 \approx 90$ ms (Camilo et al. 2002). All estimated birth periods are already significantly larger than what is expected from core-collapse theory of massive stars and it appears difficult to explain even spin periods of a few tens milliseconds (see Heger et al. 2003 for a recent review). The estimated initial spin period for PSR J0538+2817 is much larger still, placing strong constraints on the origin of birth kicks imparted on neutron stars as discussed by Romani & Ng (2003).

In summary, we have measured the proper motion of PSR J0538+2817 which clearly associates the pulsar with the SNR S147. From the separation of the pulsar from the SNR center we determine an age of $\tau = 30 \pm 4$ kyr, making the pulsar significantly younger than is indicated by its characteristic age of $\tau_c = 618$ kyr. This implies a large initial spin period of $P_0 = 139$ ms. The implied possibility of exotic cooling should be revisited after a magnetized atmosphere has been fitted to the recent X-ray data.

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Table 1. Timing parameter of PSR J0538+2817

Parameter	Value
Ecliptic longitude, λ (deg)	85.232553(3)
Ecliptic latitude, β (deg)	4.93582(4)
R.A.[a](J2000)	05 38 25.0623
DEC[a](J2000)	28 17 09.1
Epoch (MJD)	51086.0
Spin frequency, ν (s^{-1})	6.985276348019(5)
First derivative, $\dot{\nu}$ (10^{-15} s^{-2})	$-179.04753(6)$
Second derivative, $\ddot{\nu}$ (10^{-24} s^{-3})	$-0.637(2)$
Spin period, P (ms)	143.1582589118(1)
First derivative, $\dot{P}$ (10^{-15})	3.669452(1)
Dispersion Measure, DM (cm^{-3} pc)	39.814(6)
Proper motion, μ_λ (mas yr^{-1})	$-41(3)$
Proper motion, μ_β (mas yr^{-1})	47(57)
Proper motion, composite[b](mas yr^{-1})	67^{-22}_{+48}
TOA Span (MJD)	49453 – 52712
Number of TOAs	249
Timing RMS (μs)	144.2

Note. — The uncertainties in the last quoted digits are given in parenthesis.

[a]calculated from ecliptic coordinates

[b]quoted value is median of asymmetric distribution

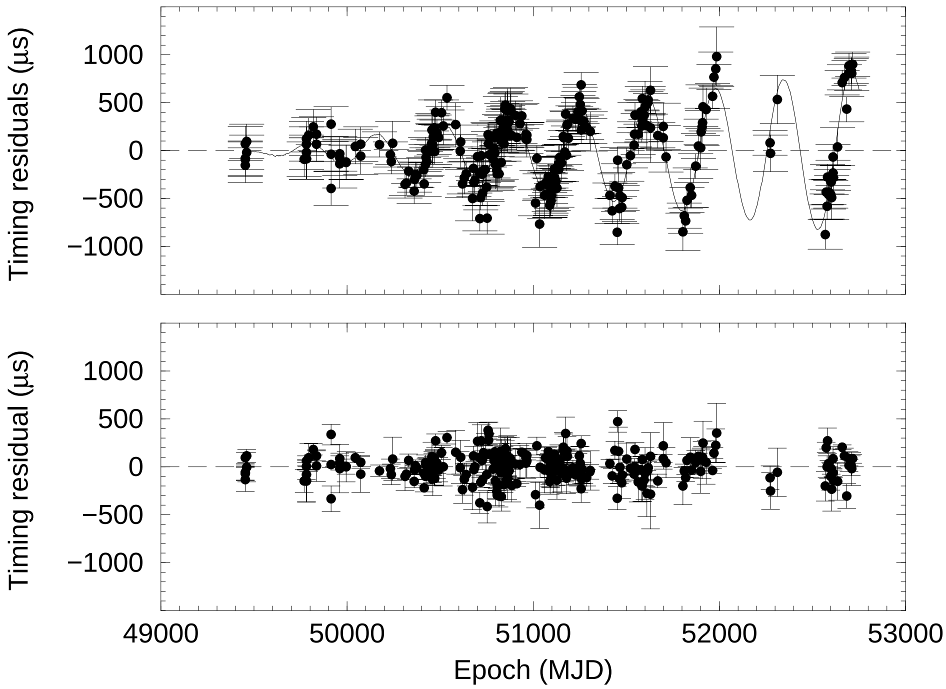

Fig. 1.— Timing residuals obtained after applying a spin-down model listed in Table 1 with a fit for proper motion (bottom) and with a corresponding proper motion set to zero (top). The solid line in the upper plot shows the expected behaviour for residuals in the latter case.

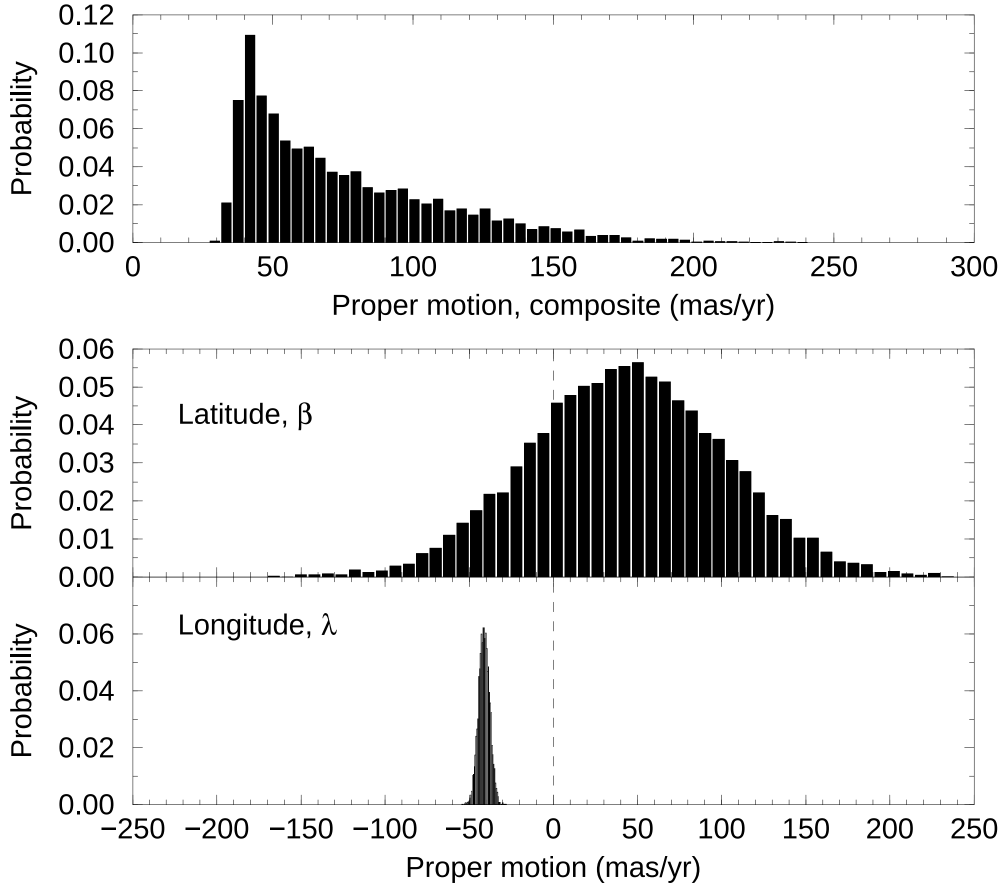

Fig. 2.— Results of Monte-Carlo simulations to determine the uncertainties in proper motion measurements.

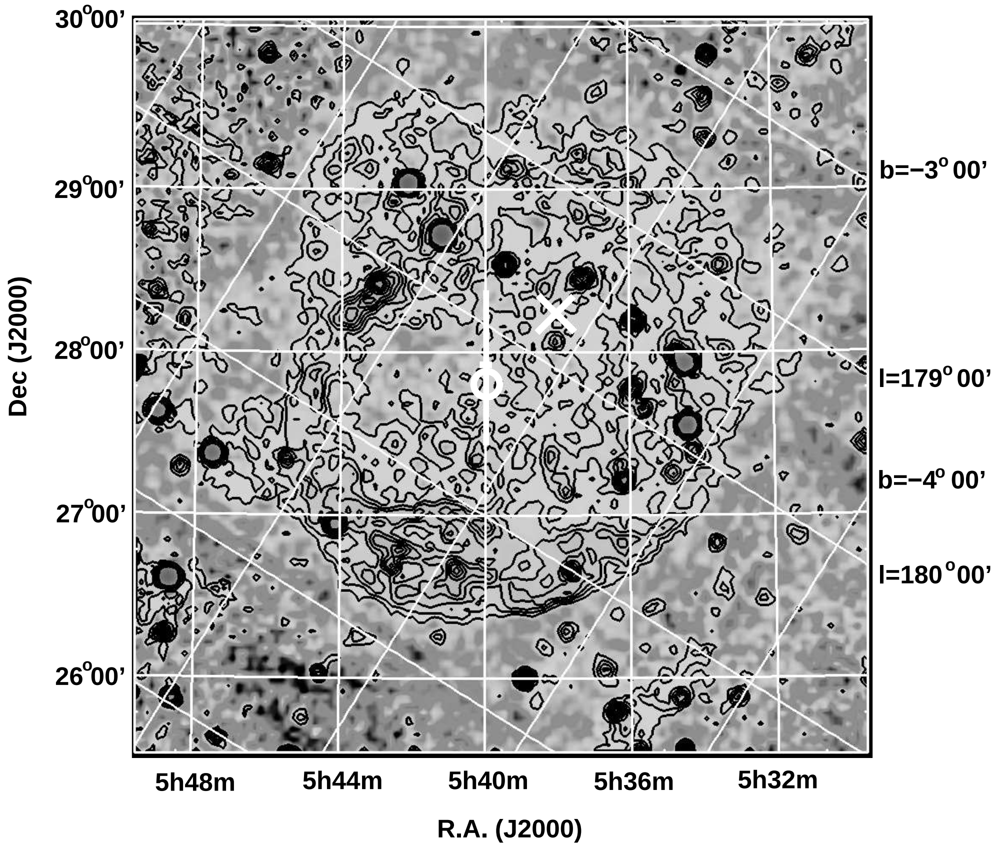

Fig. 3.— Radio image of S147 obtained at 2.7 GHz by Fürst & Reich (1986) convolved to a 5' beam. Contours are in steps of 25 mK T_B beginning at 27.5 mK T_B. The right scale indicates Galactic coordinates. The determined center of the SNR is marked by a circle, the position of PSR J0538+2817 by a 'X'. The position of the pulsar 30,000 years ago (uncertainties are marked) agrees well with the centre of the SNR.